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MEMORANDUM REPORT BRL-MR-3547

HIGH-PROGRESSIVITY/DENSITY (HPD) PROPELLING CHARGE CONCEPTS; PROGRESS OF PROGRAMMED-SPLITTING STICK PROPELLANT

Frederick W. Robbins
Albert W. Horst

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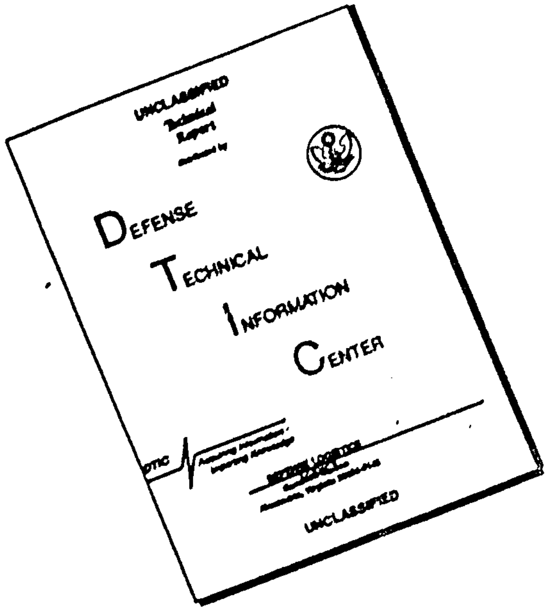

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This report summarizes progress to date on the manufacture and closed bomb evaluation of a new high-progressivity gun propellant configuration. The concept is known as programmed-splitting stick propellant and involves the use of embedded slits which are not initially exposed to hot ignition gases. Normal surface regression during burning, however, exposes the slits, typically after peak pressure has been reached in the gun, leading to a large increase in surface area and a corresponding increase in the mass generation rate. Accompanying increases in downbore pressures can lead to significant gains in muzzle velocity without any increase in maximum chamber pressure.

At the time of this review, small lots of programmed-splitting stick propellant have been manufactured and subjected to closed bomb evaluation. The results of these tests indicate a high progressivity but not to the degree theoretically predicted. The disparity is postulated to be linked to a finite voidage associated with the slits in the actual grains and its possible influence on successful closure of the ends to ignition gases and mechanical behavior of the grains during the burning process.

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TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

I. INTRODUCTION

The objective of the High-Progressivity/Density (HPD) Propelling Charge Concepts Program is to investigate the feasibility of achieving significant increases in muzzle velocity, for a given maximum pressure, over that achieved by conventional systems now being used. Moreover, this performance increase is to be obtained using existing propellant formulations and without invoking nonconventional ballistic concepts such as traveling charge or light gas guns.

The velocity achieved by a particular projectile as it exits the muzzle of a gun is principally the result of the pressure history acting on its base while it travels down the bore of the tube. The maximum pressure value allowable is usually dictated by gun tube design, but the actual pressure profile, apart from this maximum value, exerted on the projectile base is a result of the competition between the quantity of gas produced by the burning propellant and the amount of free volume available. At the beginning of the event, the projectile is not moving or is moving only very slowly, so the pressure rises rapidly as the propellant burns. However, as the projectile speeds up, it eventually creates additional volume much faster than gases are created to fill it. As a result, in virtually all cases, the pressure falls off much more rapidly than desired.

Past attempts to counter this problem have most often involved the use of propellant configurations exhibiting a continuous increase in burning surface as a function of distance burned (e.g., 7-, 19-, or even 37-perforated grains). Less conventional approaches have included consolidated propellant charges (i.e., one or more compacted aggregates of individual propellant grains), offering an increase in total available energy and the potential for an additional increase in burning surface during the ballistic event as the aggregate deconsolidates. However, programmability and reproducibility of the deconsolidation event have presented serious challenges to the charge designer.

Concepts being considered under the HPD Program include programmed-splitting, perforation-augmented burning, erosive-augmented burning, pressure-supported perforation-augmented burning, monolithic charges, programmed ignition, multiple granulations, and multi-layered propellants.

The approach to be presented in this report is based on a concept by which the increase in surface area can be programmed to commence at any particular point in the burning process, rather than being operative as soon as the propellant is ignited. Thus, a very high loading density charge can be employed without excessive burning surface and overpressurization of the gun early in the ballistic cycle. Second, this increase in surface area is, conceptually at least, unlimited. Thus, despite a desirably low initial burning surface, the programmed increase in burning surface after peak pressure can assure total burning of the charge before the projectile exits the gun, meeting the second major requirement for the use of very high loading density charges. This concept, applicable to a number of propellant configurations, has been exploited first as programmed-splitting stick propellant, and progress to date will be reported.

II. THEORETICAL

Many gun systems utilize 7-perforated granular propellant as the main propellant charge. If the same charge weight as used in the 7-perforated charge is assumed to burn such that the maximum velocity is obtained (a constant pressure calculation), a velocity increase of only about 5% over that of an optimized 7-perforated charge is predicted. Therefore, not only a near-optimum burning surface profile (i.e., extremely progressive) but also more total energy (i.e., greater charge weight) is required in order to achieve greater increases in velocity.

Particularly attractive in respect to both of these requirements is the programmed-splitting propellant concept, which effectively decouples the burning surface after peak pressure from that preceding it. This concept provides for a discontinuous increase in burning surface at any desired regression distance, at which point the burning surface reaches an embedded array of slits and the flame envelopes the additional surface area. A programmed-splitting stick (see Figure 1) was selected for initial study because it seemed to be manufacturable with current extrusion technology, to offer a very high loading density, and to provide the fault-tolerant, ignition benefits of a stick propellant configuration. The same concept can be applied to slab or scroll propellant configurations, but manufacturing problems were felt to be greater. Any of these configurations, of course, requires that the ends or edges where the slits are initially exposed be adequately inhibited to prevent the flame from prematurely reaching the slits. NOSOL 363 propellant (Lot RAD-1-2-73) was chosen for this initial effort because it is extruded without solvents and potential problems with drying would be reduced; in addition, the sheet stock was readily available.

The programmed-splitting stick propellant configuration was modeled as a cord until the slits were reached and then as long pie-shaped wedges. The slits were assumed initially to occupy no volume. The optimization process involved first determining the proper cord geometry to achieve the desired maximum pressure and then defining the slit parameters (number and dimension) to raise the pressure to this same value once again, as shown in Figure 2. Clearly, a multiplicity of such grain configurations could be employed to achieve an even greater number of peaks, approaching the optimal flat pressure-time curve. However, even the single, basic configuration with three or four slits of the same dimension (yielding six or eight pie-shaped wedges) was calculated to provide the desired increase in performance for the 155-mm howitzer.

III. MANUFACTURING EXPERIENCE

A die and stake, shown in Figure 3, were designed and fabricated for manufacturing programmed-splitting stick propellant of the calculated, nominal dimensions for the 155-mm howitzer. The stake was made by soldering four half-vanes to one whole vane, all 0.254 mm thick, making a three-vane stake. The vanes were then soldered into a base which fit into the die. Both cord propellant and programmed-splitting stick propellant were extruded for closed bomb firings. The cord propellant was made by

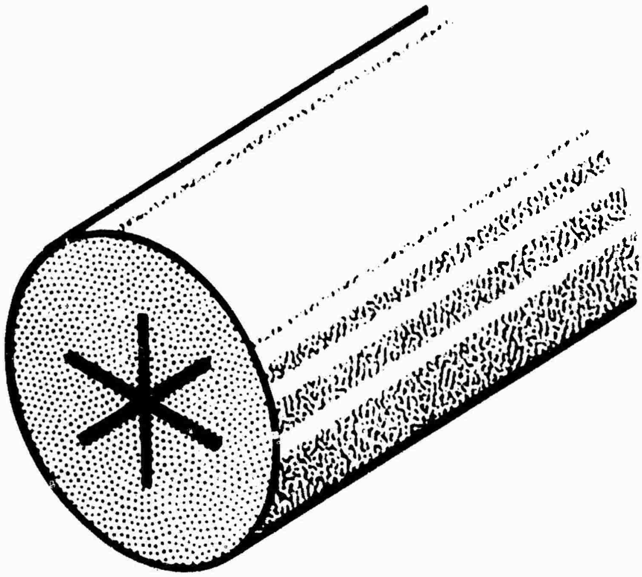

Figure 1. Programmed-Splitting Stick Propellant

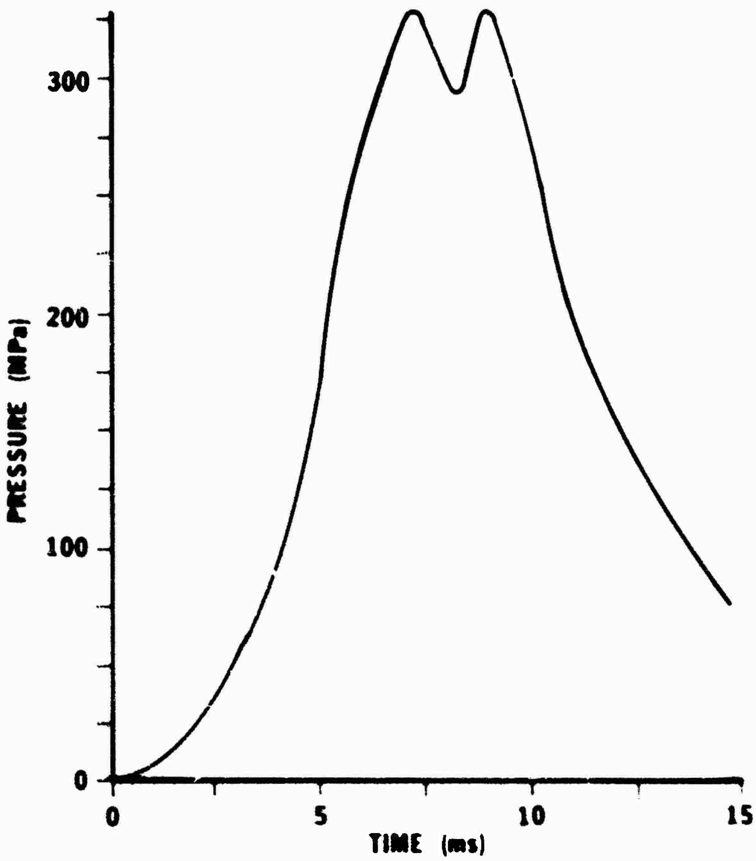

Figure 2. Calculated Pressure-Time Profile for Programmed-Splitting Stick Propellant

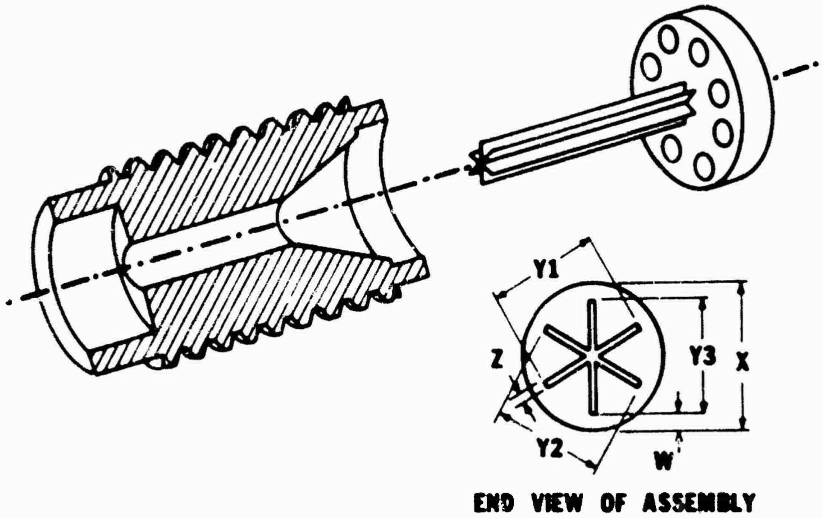

Figure 3. Die Design for Programmed-Splitting Stick Propellant

removing the stake and extruding through the same die. Both configurations expanded after extrusion, with the programmed-splitting stick expanding by 3% and the solid cord expanding 5.6% on the outside diameter.

Initial extrusions were successful in that the slits remained blind, never breaking through to the outer lateral surfaces, despite the small webs. The overall average web was 0.686 mm, but, as the vanes, once assembled to the base, were not all of the same dimension, a smaller-web region resulted where the average was 0.546 mm and the minimum was 0.483 mm. The discrepancies between the diameters associated with the die vanes and those with the resulting propellant slits varied, with the largest deviations associated with the largest vanes. Moreover, the slits in the propellant, rather than having no volume, exhibited approximately the same width as the vanes. This resulted in an internal void volume of approximately 10%. It was also noted that the edges near the center of the grains had small irregularities similar to the edge of a saw blade. Table 1 summarizes all pertinent dimensions.

After the first two-pound extrusion of NOSOL 363, the vanes were found to be loose and were resoldered. Subsequently, while attempting to extrude a sample of JA2 propellant sheet stock, the stake separated from the base. New stakes have been machined from one piece of metal but, as of the time of this writing, have yet to be tried. The procedure for defining the new stake and die dimensions was to assume that the slit diameter would remain the same as the vane diameter and that an expansion of 3% would occur in the propellant web. Further, the tips and the edges of the vanes were filed to a sharp edge in an attempt to reduce slit width.

TABLE I. SUMMARY OF DIE AND PROPELLANT DIMENSIONS

	DIE AND STAKE (FROM DRAWING) mm	DIE AND STAKE (MEASURED) mm	PROGRAMMED-SPLITTING GRAIN (MEASURED) mm (MIN) (MAX)	SOLID CORD GRAIN (MEASURED) mm (MIN) (MAX)
DIAM (X)	5.89	5.83	6.07 (5.99) (6.17)	6.22 (6.20) (6.24)
SLOT DIAM (Y1)	4.70	4.55	4.57 (4.34) (4.83)	
(Y2)	4.70	4.78	4.70 (4.47) (4.98)	
(Y3)	4.70	4.83	5.06 (4.90) (5.21)	
AVERAGE	4.70	4.72	4.78	
SLOT WIDTH (Z)	0.254	0.254	0.254	
WEB (W)	0.594 *	0.585 *	0.686 (0.483) (0.914)	

* CALCULATED

IV. EXPERIMENTAL RESULTS

Closed bomb firings were conducted in an attempt to determine whether the programmed-splitting propellant burns as mathematically modeled and to test the effectiveness of different methods of sealing the ends of the grains. Also, tests were performed statically in a high pressure oil bath to evaluate the end seals.

A closed bomb is a closed vessel with no moving boundaries in which propellant is burned. The pressure-time curve is measured, and with certain assumptions (e.g., instantaneous ignition, normal regression on all propellant surfaces, and a given mass fraction as a function of distance burned) one can deduce the rate of surface regression (i.e., the burning rate) as a function of pressure.

A 210-cc closed bomb was chosen for these studies because of the limited amount of propellant available. All samples were cut to 9.6 cm in length, the longest the bomb would accommodate. Configurations tested were both cord and programmed-splitting, the latter with a variety of end conditions, including open-ended, asphalt-covered, acetone-solvated, acetone-solvated covered with collodion, covered with a small aluminum cap, and capped with NOSOL 363 discs bonded with an isocyanate crosslinking agent. In addition, a previously extruded, single-perforated grain of the same composition but a different length was tested to allow comparison with past results.

Since the closed bomb data reduction program does not include a form function to describe programmed-splitting configurations, the analysis was performed assuming the grain to be a solid cord, yielding an apparent burning rate. However, by assuming the burning rates obtained for the sample of actual cord propellant to be applicable to the programmed-splitting grains as well, we were able to deduce burning surface profiles from the mass-generation rate data, revealing more directly the behavior of the programmed-splitting event. Theoretically, the apparent burning rate curves should have resembled Figure 4 and the surface area profiles should have looked like Figure 5.

A problem was encountered in the reduction of closed bomb data because of the internal voidage associated with the blind slits. There were 21 grains used in each firing, but the computer program calculated (from the density, mass of propellant, and grain dimensions) that there were approximately 19 grains. This led to apparent burning rates and surface areas which were higher at all points than theoretically expected; however, it should not have changed the shape of the curves.

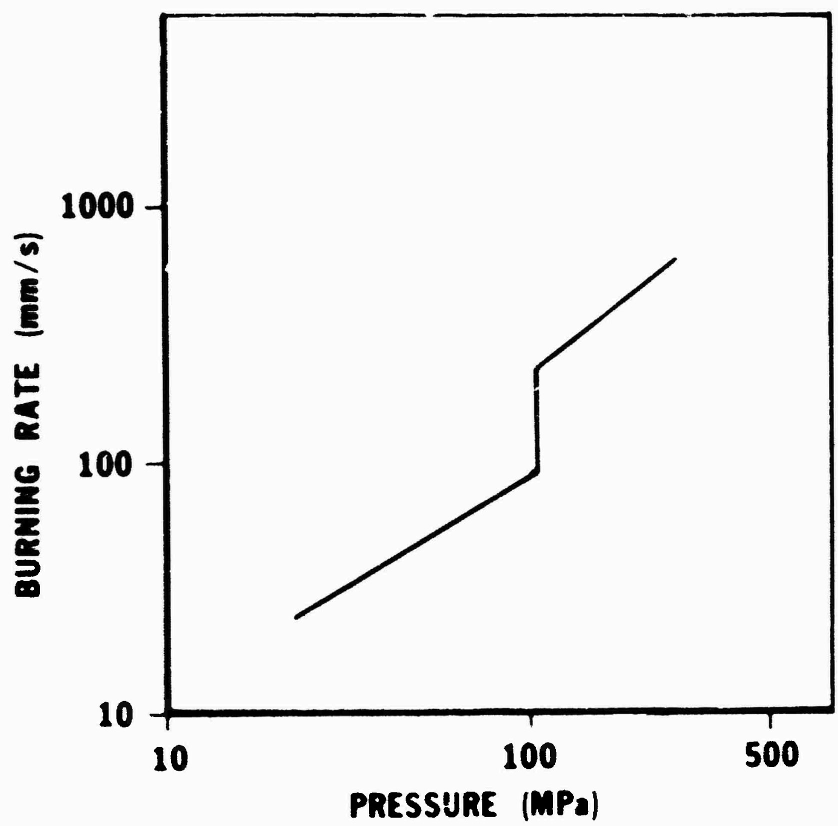

Figure 4. Theoretical Apparent Burning Rate Profile for Programmed- Splitting Stick Propellant

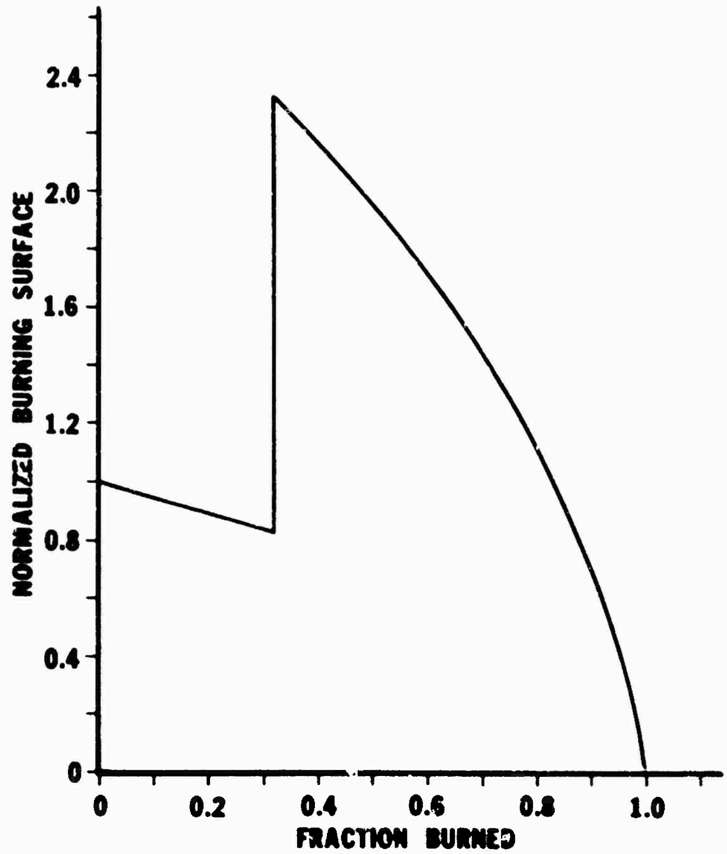

Figure 5. Theoretical Surface Profile for Programmed-Splitting Stick Propellant

Another problem with the reduction technique which could have changed the shape of the curves was the smoothing technique applied to the pressure-time output from the closed bomb firings. Such procedures tend to smooth out any abrupt changes, such as that expected with a discontinuous increase in surface area. To probe this concern, a computer-generated pressure-time curve (generated using a true, programmed-splitting form function) was smoothed in the same manner as the real output from a closed bomb firing. Indeed, the expected, abrupt changes in the reduced data were rounded but not to a degree that would prevent recognition of the splitting event.

The burning rates for the cord, shown in Figure 6, and for the single-perforated granulations were consistent and also agreed well with previous NOSOL 363 closed bomb data. These burning rates were therefore used as the baseline and for the reduction of all burning surface profiles.

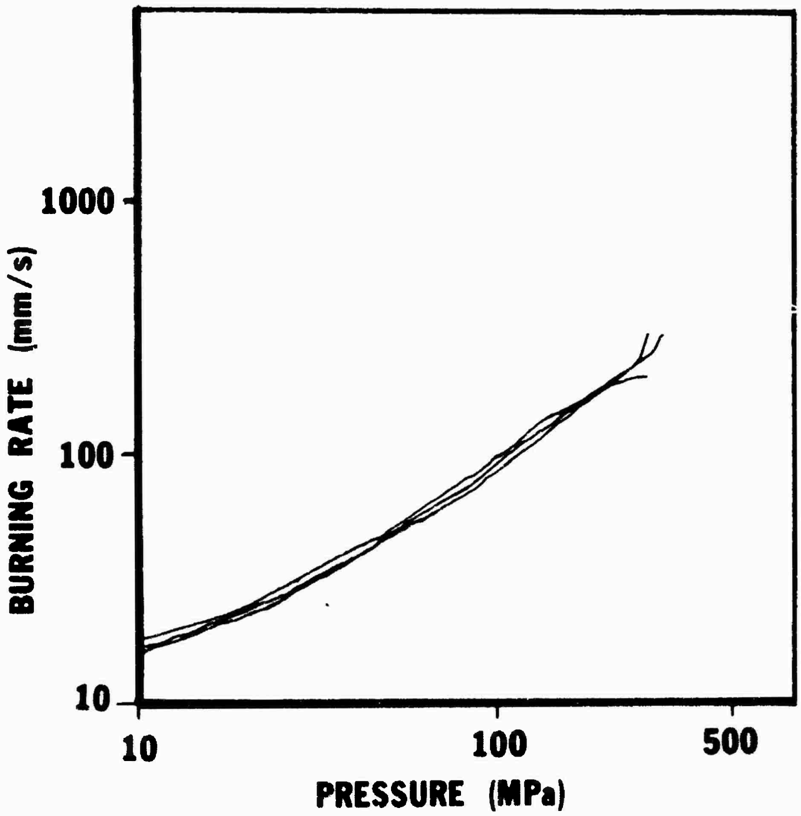

Figure 6. Burning Rates for Solid Strands of NOSOL 363 Propellant

The apparent burning rates for the open-ended, programmed-splitting configuration (reduced as a cord) showed considerable variability in the 7-35 MPa pressure range and, as expected, manifested about a 3-fold increase over the burning rates of the cord for the entire pressure range (see Figure 7). The accompanying burning surface profiles are provided in Figure 8. Figure 9 displays the apparent burning rates for the sample with asphalt-covered ends. Figure 10 presents the apparent burning rates for the sample whose ends had been solvated in acetone to close the slits, and Figure 11 shows the corresponding surface profiles. A comparison of the averaged values of the burning rates for the cord and the apparent burning rates for the three programmed-splitting samples is shown in Figure 12.

Other attempts at closing off the ends of the blind slits in the programmed-splitting propellant samples, such as the use of aluminum end caps and NOSOL 363 discs as mentioned earlier, were no more effective than just solvating the ends with acetone. The discussion will therefore be centered around the configuration with acetone-solvated ends.

Grains with acetone-solvated ends similar to those used in the closed bomb studies were also pressurized slowly in an oil bath, in 70-MPa increments, to over 500 MPa. The samples were inspected after each increment of pressurization. One out of the ten pressurized had oil in the voidage after the first 70 MPa; the rest all remained intact with no oil in the voidage over the entire pressure range.

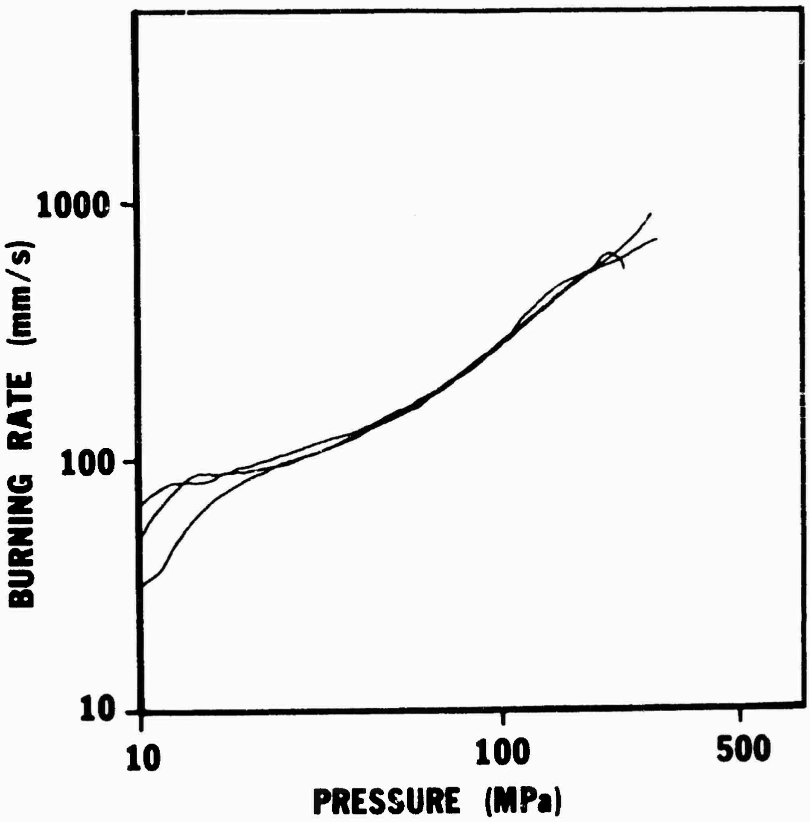

Figure 7. Apparent Buring Rates for Programmed-Splitting Stick Propellant with Open Ends

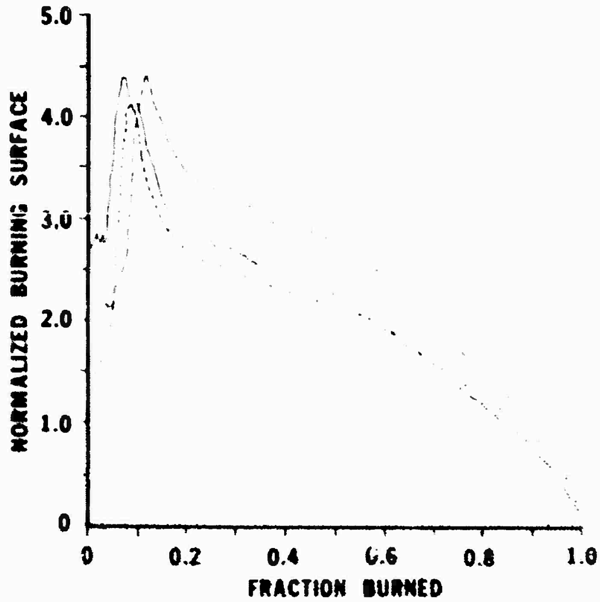

Figure 8. Burning Surface Profiles for Programmed-Splitting Stick Propellant with Open Ends

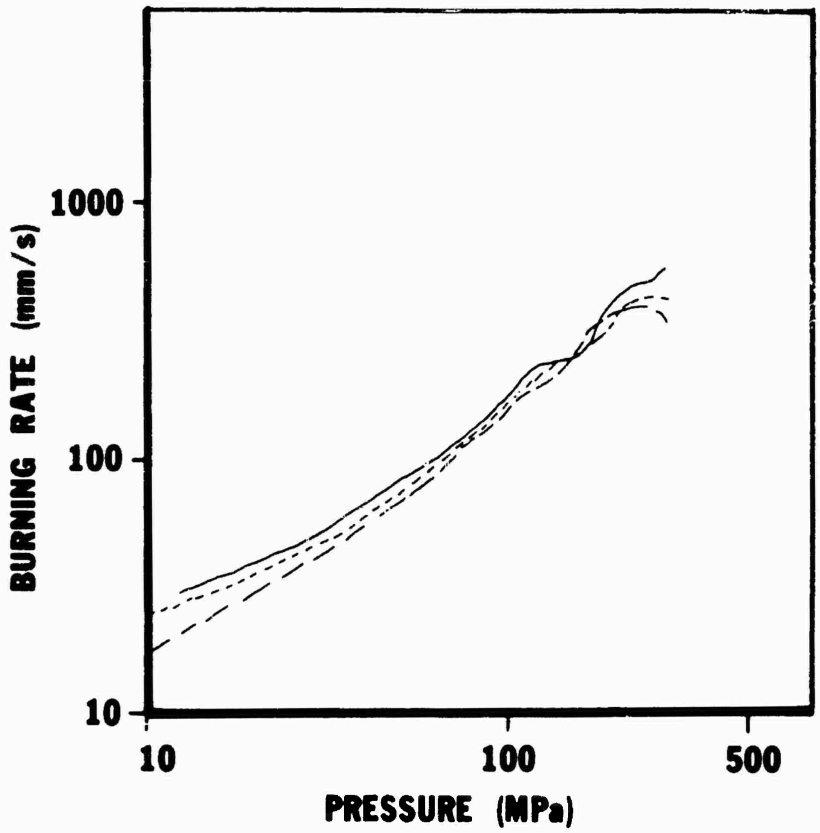

Figure 9. Apparent Burning Rates for Programmed-Splitting Stick Propellant with Asphalt-Covered Ends

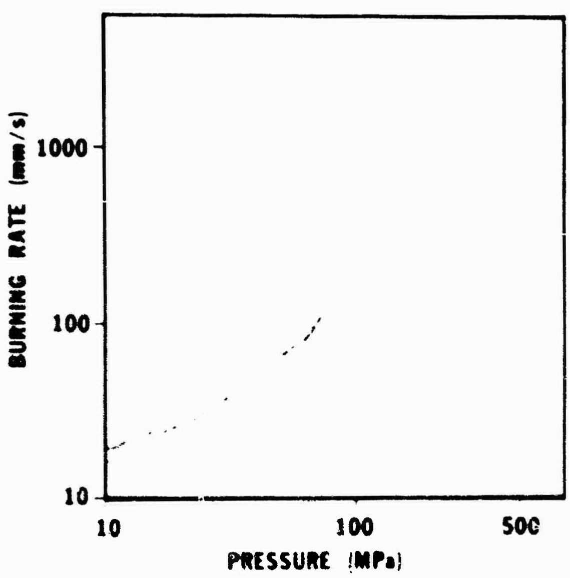

Figure 10. Apparent Burning Rates for Programmed-Splitting Stick Propellant with Acetone-Solvated Ends

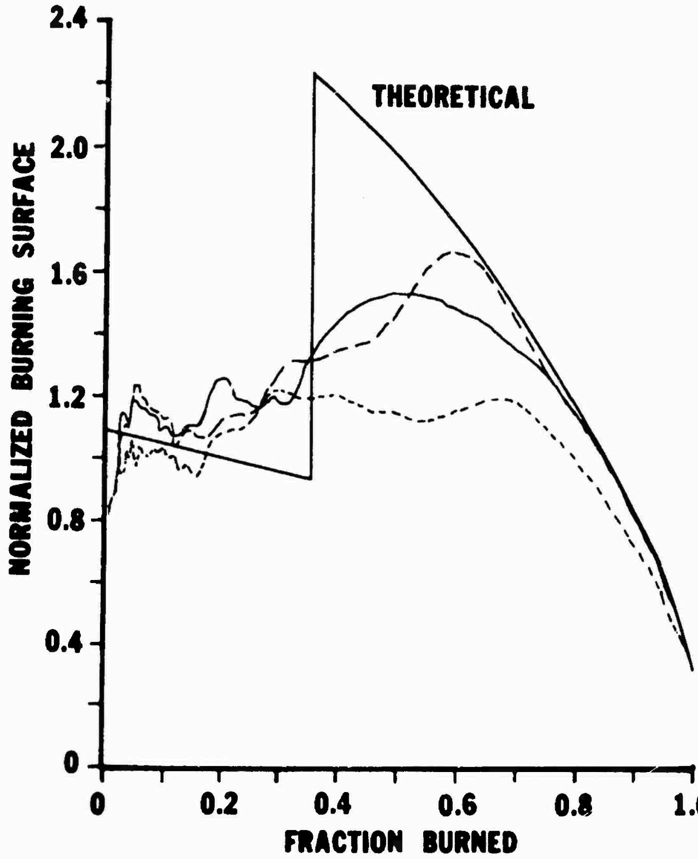

Figure 11. Burning Surface Profiles for Programmed-Splitting Stick Propellant with Acetone-Solvated Ends

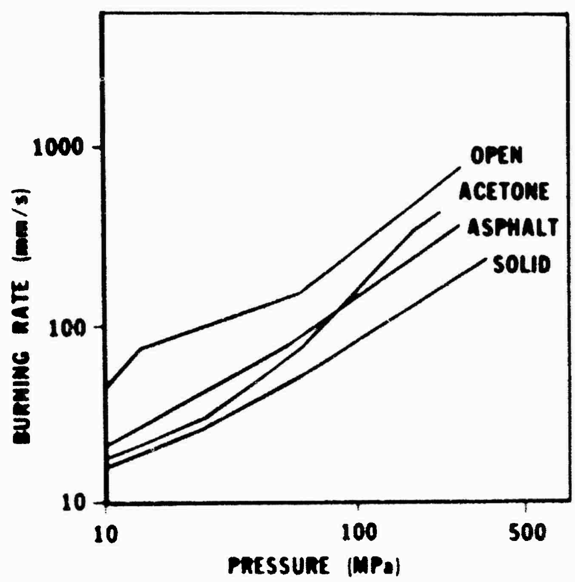

Figure 12. Averaged Apparent Burning Rates

V. DISCUSSION

Successful application of the programmed-splitting stick propellant concept in the gun environment requires that the discontinuous increase in surface area must occur only after maximum pressure has occurred. This, in turn, requires that the flame not reach the blind slits prematurely (i.e., by any means except the planned burn-through of the web). The flame must be prevented from entering the ends of the grains and the grain must not break, opening a path to the blind slits. Therefore, most of the discussion will address this aspect of the problem.

From Figure 12, it would appear that the asphalt covering did not prevent the flame from getting to the slits since the apparent burning rates for that sample are higher in the low pressure region than for the cords or the sample with acetone-solvated ends. The asphalt seems, however, to have acted as an inhibitor on the ends themselves, since the apparent burning rates are not as high as for the open-ended grains. Further, no progressivity is revealed, as the curves for the samples with asphalt-covered and open ends are nearly parallel to that for the cord propellant.

Figure 12 shows a small increase in the apparent burning rates at low pressures for the samples with acetone-solvated ends. This is not, however, totally unexpected since the reduction procedure will, because it ignores the presence of voidage in the slit region, underestimate the total number of grains (and accompanying initial surface) and therefore overestimate the apparent burning rates by about 10%. We further expect to see the apparent burning rates increasing faster than for the cord propellant and the curve then becoming parallel to that for the open-ended grains. What is surprising is that the burning rate curve should start to rise at such a low pressure (50 MPa) and continue to exhibit progressivity long after expected web burn-through at about 125 MPa!

We next call attention to the burning surface profile for this same sample with acetone-solvated ends, shown in Figure 11 along with a theoretical profile for the programmed-splitting grain. The surface profile seems to be a much better discriminator for the processes of interest to us here. Again we see an early increase around 50 MPa, followed by incremental increases until the curve approaches the theoretical curve at a point long after web burn-through should have occurred.

There are three effects which could have been responsible for the unexpected, early rise in the apparent burning rates and the burning surface profile. They are data-smoothing during the reduction procedure (mentioned earlier), variations in the web, and early exposure of some portion of the blind slits. In order to study each of these possibilites, calculations were made with a computer code to simulate the programmed-splitting configuration burning in a closed bomb. The form function was programmed to assume burning on lateral and end surfaces until web burn-through and then on the remaining long, pie-shaped wedges. It was also assumed that the slits occupied no volume. The resultant pressure-time curve served as input to the existing closed bomb data reduction program, and apparent burning rates and surface areas were calculated using minimal smoothing (no smoothing on the pressure-time curve and a 5-point smoothing bridge to obtain dp/dt) and then with the normal smoothing procedure (a 25-point smoothing bridge on the pressure-time curve and a 15-point bridge to obtain dp/dt). The apparent burning rate curves are shown in Figure 13, and the surface area ratio curves are displayed in Figure 14. It is apparent that smoothing was not responsible for the unexpected closed bomb results.

Other synthetic runs were performed to investigate the possibility of the web variation being large enough to account for this effect. A run was made with 1/3 of the charge weight having a web equal to the smallest measured web (0.483 mm) and the rest of the charge having the average of the smallest web (0.546 mm). An increase in surface area was then indicated at approximately twice the mass fraction burned (which translates also into twice the closed bomb pressure) as that where the observed, apparent burning rate curve started to rise. Even in combination with smoothing effects, this did not provide an explanation for observed behavior.

A third series of synthetic runs was made with 1/3 of the charge configured such that burn-through of the web occurred at 50 MPa and the remaining portion having a web of 0.546 mm (the average of the smallest web). These conditions, of course, reproduced the observed, early increase in the burning surface, but they also delayed burn-through of the 0.546-mm web until a pressure which was some 35 MPa higher than the value where burn-through for a 0.545-mm web would have taken place. This result approximated what we saw in the surface profiles for the samples with acetone-solvated ends, and, along with the static test results indicating grain survivability at high pressures, is consistent with an explanation for the observed closed bomb results based on early flame penetration into a significant portion but not a majority of the blind slits.

Many other problem areas remain to be investigated, including the effects of aging on any successful end-closure techniques, sensitivity of performance to web variations, the influence of propellant mechanical properties, and temperature effects. At the same time, alternative HPD concepts warrant consideration in the near future.

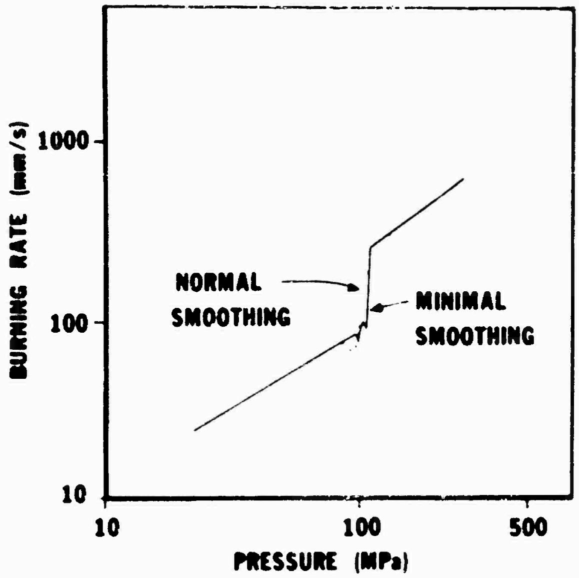

Figure 13. Apparent Burning Rates Reduced From a Synthetic Pressure-Time Profile

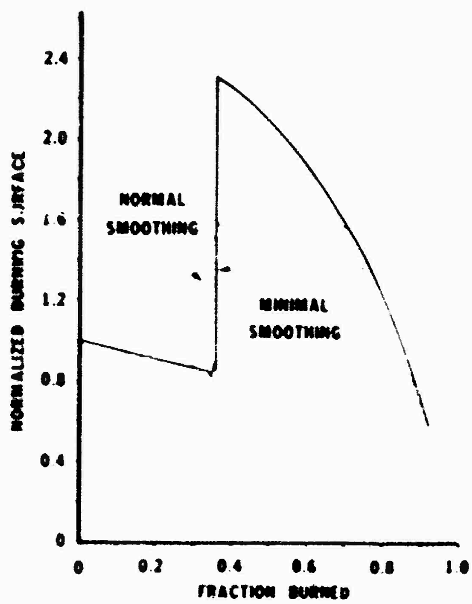

Figure 14. Burning Surface Profile Reduced from a Synthetic Pressure-Time Profile

CONCLUSIONS

Substantial performance gains are theoretically possible from rather straight-forward HPD propulsion concepts using existing propellant technology.

The feasibility of manufacturing a programmed-splitting stick propellant has been demonstrated using existing extrusion technology.

Techniques for sealing the ends of programmed-splitting stick propellant have been partially demonstrated, offering significant hope for demonstrating this HPD concept in the gun environment within the coming year.

ACKNOWLEDGMENTS

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